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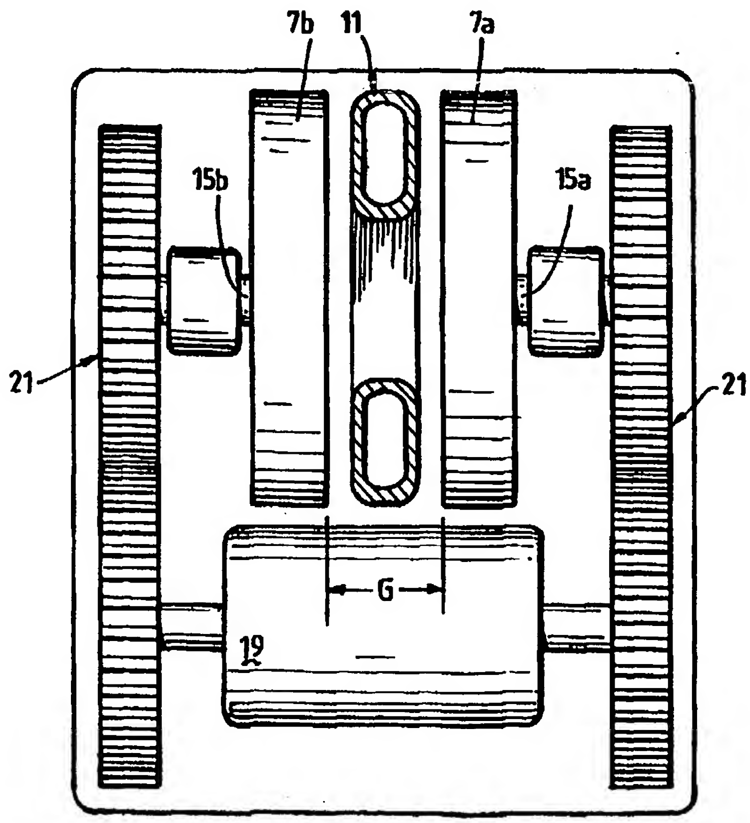
(54) Title: METHOD AND APPARATUS FOR CONTROLLING THE FLOW OF A LIQUID

(57) Abstract

An apparatus for controlling the flow of a conductive liquid through a passageway (3) is disclosed. The apparatus comprises a means for generating a magnetic field transverse to a required direction of flow of the conductive liquid in the passageway. The apparatus also comprises a means to cause rotation of the magnetic field about an axis to move the magnetic field along the length of a section of the passageway (3) with the magnetic field transverse to the required flow direction.



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METHOD AND APPARATUS FOR CONTROLLING THE FLOW OF A LIQUID

The present invention relates to a method and an apparatus for controlling the flow of an electrically conductive liquid in a passageway that is based on applying an electromagnetic force to the conductive liquid.

The present invention relates particularly, although by no means exclusively, to a method and an apparatus for electromagnetically pumping liquid metals and alloys in a passageway.

This is not the only application of the present invention and, by way of example, the present invention relates to electromagnetically braking liquid metals and alloys in a passageway.

The term "passageway" is understood to mean any suitable pipe, duct, channel or the like for conveying conductive liquids.

The term "electromagnetic force" is understood herein to mean the force generated in a conductive liquid by the interaction of an electric current in the conductive liquid and a magnetic field.

Electromagnetic force is described by the vector equation:

$$f = J \times B$$

where f is the electromagnetic force per unit volume exerted on an element of the conductive liquid, J is the

current density at the point where the element is located, and B is the magnetic field strength at the point.

The electromagnetic force f will be in a direction perpendicular to both the magnetic field and the direction of current flow and will be non-zero as long as there is a component of the magnetic field that is perpendicular to the current. The current may be generated by an external voltage or, alternatively, induced in the conductive liquid as a result of a variation in the magnetic field with time.

The use of an electromagnetic force to pump conductive liquids, such as liquid metals, is known.

Induction pumps and conduction pumps are examples of known electromagnetic pumps.

Induction pumps operate by generating a travelling magnetic field along a straight section of a pipe or channel containing a conductive liquid and thereby inducing electric currents in the conductive liquid. The currents interact with the magnetic field in accordance with the above equation to generate a net force to move the conductive liquid along the length of the pipe or channel.

Conduction pumps operate by providing a static magnetic field at right angles to the axis of a pipe or channel containing a conductive liquid and by applying an electric current from an external source to the conductive liquid via electrodes embedded in the pipe or channel. As a result, the conductive liquid forming the current path at any instance is subject to a force in a direction along the length of the pipe or channel in accordance with the above equation.

The pressure or static head which can be generated by an induction pump is related to the magnetic flux density at right angles to the flowing liquid, and to the component of electric current at right angles to the flux. A problem with known electromagnetic pumps has been the inability to generate a high static head due to the low flux densities achieved for instance using linear motor technology. The low coupling efficiency is most evident in the case of high volume pumping, where large magnet gaps are required.

An object of the present invention is to provide a method and an apparatus for electromagnetically pumping conductive liquids which alleviates the problem described in the preceding paragraph.

According to the present invention there is provided an apparatus for controlling the flow of a conductive liquid through a passageway, which apparatus comprises:

(a) a means for generating a magnetic field transverse to a required direction of flow of the conductive liquid in the passageway; and

(b) a means to cause rotation of the magnetic field about an axis to move the magnetic field along the length of a section of the passageway with the magnetic field transverse to the required flow direction.

In use, in a pumping application, the relative movement of the magnetic field and the conductive liquid generates an electric current in the conductive liquid, and the magnetic field and the electric current interact in accordance with the equation set out above to generate an

electromagnetic force to move the conductive liquid along the passageway in the flow direction.

The applicant has found that the above apparatus is an effective means of electromagnetically generating a high static head with conductive liquids and of controlling the pressure and hence the flow rate.

It can readily be appreciated that the apparatus can be used bi-directionally and, in addition to pumping a conductive liquid, can be used to apply a braking force to the liquid.

The magnetic field generating means may comprise any suitable means such as permanent magnets or electromagnets.

It is preferred that the magnetic field generating means comprise a plurality of permanent magnets.

In the pumping application of the present invention, it is preferred that the rotation means be adapted to rotate the magnetic field so that at least a component of the magnetic field moves in the flow direction.

In the braking application of the present invention it is preferred that the rotation means be adapted to rotate the magnetic field so that at least a component of the magnetic field moves in the opposite direction to the flow direction.

The rotation means may comprise one or more rotors arranged to support the permanent magnets and to rotate about the axis.

With such an arrangement it is preferred that the magnets be mounted to each rotor with adjacent poles of the magnets being of opposite polarity. As a consequence, the magnetic flux density varies sinusoidally around the circumference of each rotor.

It is preferred particularly that the magnets be arranged in a circular array on each rotor.

It is preferred that there be as small as possible spacing between adjacent magnets in the array.

It is preferred that the magnets be disk shaped.

It is preferred that the magnetic field generating means comprise a backing member for the magnets formed from a high permeability material, such as mild steel, to improve the magnetic field path.

It is preferred particularly that the rotation means comprises two rotors, with each rotor carrying a plurality of the magnets, and the rotors being spaced apart so that there is a gap G between the magnets of one rotor and the magnets of the other rotor, and the magnets being arranged so that each magnet of one rotor faces a respective one of the magnets of the other rotor, with the facing poles of the magnets being of opposite polarity.

It is preferred that the ratio of the diameter of the magnets and the gap G between the rotors be at least 1:1.

It is preferred particularly that the ratio of the diameter of the magnets and the gap G between the rotors be at least 1.5:1.

With such an arrangement it is preferred that the pump section of the passageway extend through the gap.

In one embodiment it is preferred that the rotation means comprises, a drive shaft that supports both rotors and extends through the gap between the rotors, and a motor means to rotate the drive shaft about its longitudinal axis.

In another embodiment it is preferred that the rotation means comprises, a separate drive shaft for each rotor, and a motor means to rotate the drive shafts.

The passageway may be of any suitable shape and be formed from any suitable material.

It is preferred that the shape be selected to maximise the length of the pump section of the passageway that is subject, in use, to the rotating magnetic field transverse to the required flow direction.

It is preferred particularly that the pump section of the passageway be U-shaped.

According to the present invention there is also provided a method of controlling the flow of a conductive liquid through a passageway, which method comprises:

(a) generating a magnetic field transverse to a direction of flow of the conductive liquid in the passageway; and

(b) rotating the magnetic field about an axis to move the magnetic field along the length of a section of the passageway with the magnetic field transverse to the flow direction to generate an electric current

which interacts with the magnetic field to produce an electromagnetic force to control the flow of the conductive liquid along the passageway in the flow direction.

It is preferred that the method comprises rotating the magnetic field so that a least a component of the magnetic field moves in the flow direction to pump the liquid in the flow direction.

In an alternative embodiment it is preferred that the method comprises rotating the magnetic field so that at least a component of the magnetic field moves in the opposite direction to the flow direction.

The present invention is described further by way of example with reference to the accompanying drawings, of which:

Figure 1 is a side elevation of one embodiment of the apparatus of the present invention;

Figure 2 is a cross-section along the line 2-2 in Figure 1;

Figure 3 is a vertical cross-section through a lower portion of the U-shaped section of the pipe which forms part of the apparatus shown in the Figures which illustrates the flow of current induced in conductive liquid in the pipe in use of the apparatus as a pump; and

Figure 4 is top plan view of another embodiment of the apparatus of the present invention.

The embodiment of the apparatus shown in Figures 1 and 2 is arranged to pump a conductive liquid, such as molten zinc or copper, through a pipe 3 in the direction of

the arrows marked X in Figure 2. It is noted that the present invention is not limited to this application and could be used to brake the flow of the liquid through the pipe 3.

The apparatus comprises 2 circular arrays of permanent magnets 5 formed from Neodymium/Boron/Iron or any other suitable material supported by rotors 7a, 7b which, in use, are rotated about a central horizontal axis 9. The magnets 5 are disk shaped and have a diameter that is as large as possible given the size of the rotors 7a, 7b and are arranged with a spacing that is as small as possible between adjacent magnets. The rotors 7a,7b are spaced-apart so that the opposed faces of the magnets 5 are separated by a gap G. The magnets 5 on the rotors 7a, 7b are arranged in pairs with each magnet 5 on rotor 7a facing a magnet 5 of opposite polarity on rotor 7b. As a consequence, a series of magnetic fields extend across the gap G. In addition, the magnets 5 are arranged on each rotor 7a, 7b with adjacent magnets 5 having opposite polarities. As a consequence, the magnetic flux density varies approximately sinusoidally around the circular arrays.

As can best be seen in Figure 2, a U-shaped section 11 of the pipe 3 is arranged to extend into the gap G so that, in use, a conductive liquid in the U-shaped section 11 is subject to the magnetic fields produced by the pairs of magnets 5 on the rotors 7a, 7b.

In order to improve the magnetic field strength of the magnets 5, an annular ring of mild steel, or other suitable high permeability material, is provided as a backing member for the magnets 5 on each rotor 7a, 7b.

The rotors 7a, 7b are mounted on a drive shaft 15 which extends through the gap G. A 3 phase motor 19 is

coupled to one end of the drive shaft 15 and the motor 19 is operable to rotate the drive shaft 15 to thereby move the magnets 5 about the axis 9 in the direction of the arrow Y in Figure 2.

In use, the effect of the rotating magnetic fields between the pairs of magnets 5 is to induce circulating electric currents in the conductive liquid at that time in the U-shaped section 11 of the pipe 3. In accordance with the equation set out above, the magnetic fields and the electric currents interact to produce an electromagnetic force which acts on the conductive liquid to pump the conductive liquid through the section 11 of the pipe in the direction of the arrows X in Figure 2. The flow of the induced currents is illustrated in Figure 3, and it is the radial components of the currents that contribute to the pumping effect.

In accordance with the equation set out above, the electromagnetically produced force is proportional to the magnetic flux density and to the magnitude of the induced current. Since the magnitude of the current is proportional to the flux density also, this means that the force is proportional to the square of the flux. The force is also a function of the spatial rate of change of flux in the direction of motion. Important structural factors that have an effect on the magnetic flux density include the size of the gap G between the magnets 5 and the ratio of the magnet face versus gap size. The applicant found that good results were achieved in laboratory experiments with a U-shaped section 11 positioned in gaps G of between 15 and 30 mm.

In the final analysis, an important feature of the pump is that the pressure or static head of the conductive liquid be proportional to the rate of rotation of the magnets 5.

The embodiment shown in Figure 3 is conceptually similar to that shown in Figures 1 and 2, and the main difference is that the rotors 7a, 7b are mounted to separate aligned drive shafts 15a, 15b, and the drive shafts 15a, 15b are separately coupled via gear drives 21 to a motor 19. The advantage of this arrangement is that the U-shaped section 11 of the pipe 3 is the only component that occupies the gap G between the magnets 5.

The laboratory experiments referred to above were carried out by the applicant principally to test the key relationships governing the apparatus of the present invention when used in the pump application.

The laboratory experiments were carried out on a pump of the type shown in Figures 1 and 2 and comprised measuring the static head generated by the pump at varying gaps G between the magnets 5 and varying rotational speeds of the rotors 7a, 7b.

This was achieved by pumping Indalloy (Bi 49%, Pb 18%, Sn 12%, In 21%), an alloy with a melting point of 57°C, $1.25 \times 10^6\ \Omega^{-1}m^{-1}$ conductivity and 9100 kg/m^3 density, through the pump. The rotors 7a, 7b were 210 mm in diameter and there were 8 magnets 5 on each rotor 7a, 7b. The rotors 7a, 7b were located on a keyed shaft 15 such that the spacing between the pole faces could be easily adjusted. Two U-shaped pipe sections 11 were tested, one from a non-conductive high strength glass-epoxy resin and the second from stainless steel.

The pump was arranged so that molten Indalloy contained in a small tank was fed vertically downwards into the pump. A pipe (not shown) of 4 m length was connected vertically at the pump outlet. The pumping head was measured through the displacement of a float inserted into

the exit pipe. Several sets of measurements were taken at increasing and decreasing rotor speeds. The static head achieved at a fixed rotor speed was found to be repeatable and was measured to an accuracy of ±0.5 mm. Rotational speed was measured using a digital tachometer to an accuracy of better than ±0.5 RPM. The measurement procedure was repeated using a number of magnet gaps G for both the conductive and non-conductive pipe sections 11. At 3 magnet gaps G, measurements were taken of the magnetic field strength over a plane lying at the midpoint of the pole separation. The pressure developed was found to be proportional to the velocity of the magnetic field through the Indalloy and thus provides simple and precise control of the pumping process.

Disk Separation (mm)	Peak Magnetic Field (T)	Measured Pressure (kPa) At 500 RPM
19	0.61	96.8
24	0.52	65.7
29	0.45	44.2

Table 1: Measured Pump Performance

Table 1 shows the measured pump pressure at 3 magnet gaps G. The pump was operated to a speed of 2000 RPM and the torque and power required were easily supplied by a conventional 5.5 kW 3-phase 4-pole motor. An increase of between 2-16% in static head was measured when the non-conductive U-tube was replaced with a stainless steel tube of the same design.

The laboratory experiments also found that the ratio of the diameter of the magnets 5 and the gap G between the rotors 7a, 7b should be at least 1:1 for optimum performance. Specifically, the applicant found that performance dropped off quickly at ratios less than 1:1.

The results of the laboratory experiments indicate that the apparatus of the present invention when used as a pump is an effective means of delivering liquid metals. The results are such that the applicant believes that the pump operates at significantly reduced power requirements, when compared with those based on conventional pumps.

Many modifications may be made to the preferred embodiments of the present invention described above without departing from the spirit and scope of the present invention.

For example, whilst the embodiments shown in Figures 1 to 3 comprise twin rotors 7a, 7b, it can be readily appreciated that the present invention is not so limited and extends to single rotor arrangements.

Furthermore, whilst the embodiments comprise permanent magnets 5 arranged in a circular array on the rotors 7a, 7b, it can be readily appreciated that the present invention is not so limited and extends to the use of electromagnets and permanent magnets arranged in any suitable array.

Furthermore, whilst the embodiments comprise a U-shaped section 11 of pipe 3, it can readily be appreciated that the present invention is not so limited and extends to any suitable shape of section of pipe 3. By way of example, the present invention extends to the use of

rotating magnetic fields in relation to straight and 90° curve sections of pipes.

CLAIMS:

1. An apparatus for controlling the flow of a conductive liquid through a passageway, which apparatus comprises:

(a) a means for generating a magnetic field transverse to a required direction of flow of the conductive liquid in the passageway; and

(b) a means to cause rotation of the magnetic field about an axis to move the magnetic field along the length of a section of the passageway with the magnetic field transverse to the required flow direction.

2. The apparatus defined in claim 1 wherein the rotation means is adapted to rotate the magnetic field so that at least a component of the magnetic field moves in the flow direction to pump the liquid in the flow direction.

3. The apparatus defined in claim 1 wherein the rotation means is adapted to rotate the magnetic field so that at least a component of the magnetic field moves in the opposite direction to the flow direction to brake the flow of the liquid.

4. The apparatus defined in claim 2 or claim 3 wherein the magnetic field generating means comprises a plurality of magnets.

5. The apparatus defined in claim 4 wherein the rotation means comprises one or more rotors arranged to support the magnets and to rotate about the axis.

6. The apparatus defined in claim 5 wherein the magnets are mounted to each rotor with adjacent poles of the magnets being of opposite polarity.

7. The apparatus defined in claim 4 or claim 5 wherein the magnets are arranged in a circular array on each rotor.

8. The apparatus defined in claim 7 wherein there is as small as possible spacing between adjacent magnets in the array.

9. The apparatus defined in claim 7 or claim 8 wherein the magnets are disk shaped.

10. The apparatus defined in any one of claims 4 to 9 wherein the magnetic field generating means comprises a backing member for the magnets formed from a high permeability material, such as mild steel, to improve the magnetic field path.

11. The apparatus defined in claim 9 wherein the rotation means comprises two rotors, with each rotor carrying a plurality of the magnets, and the rotors being spaced apart so that there is a gap G between the magnets of one rotor and the magnets of the other rotor, and the magnets being arranged so that each magnet of one rotor faces a respective one of the magnets of the other rotor, with the facing poles of the magnets being of opposite polarity.

12. The apparatus defined in claim 11 wherein the ratio of the diameter of the magnets and the gap G between the rotors is at least 1:1.

13. The apparatus defined in claim 11 or claim 12 wherein the section of the passageway extends through the gap.

14. The apparatus defined in claim 13 wherein the rotation means comprises, a drive shaft that supports both rotors and extends through the gap between the rotors, and a motor means to rotate the drive shaft about its longitudinal axis.

15. The apparatus defined in claim 13 wherein the rotation means comprises, a separate drive shaft for each rotor, and a motor means to rotate the drive shafts.

16. The apparatus defined in any one of the preceding claims wherein the shape of the passageway is selected to maximise the length of the pump section of the passageway that is subject, in use, to the rotating magnetic field transverse to the required flow direction.

17. The apparatus defined in claim 16 wherein the pump section of the passageway is U-shaped.

18. A method of controlling the flow of a conductive liquid through a passageway, which method comprises:

(a) generating a magnetic field transverse to a direction of flow of the conductive liquid in the passageway; and

(b) rotating the magnetic field about an axis to move the magnetic field along the length of a section of the passageway with the magnetic field transverse to the required flow direction to generate an electric current which interacts with the magnetic

field to produce an electromagnetic force to control the flow of the conductive liquid along the passageway in the flow direction.

19. The method defined in claim 18 comprises rotating the magnetic field so that at least a component of the magnetic field moves in the required flow direction to pump the liquid in the flow direction.

20. The method defined in claim 18 comprises rotating the magnetic field so that at least a component of the magnetic field moves in the opposite direction to the flow direction.

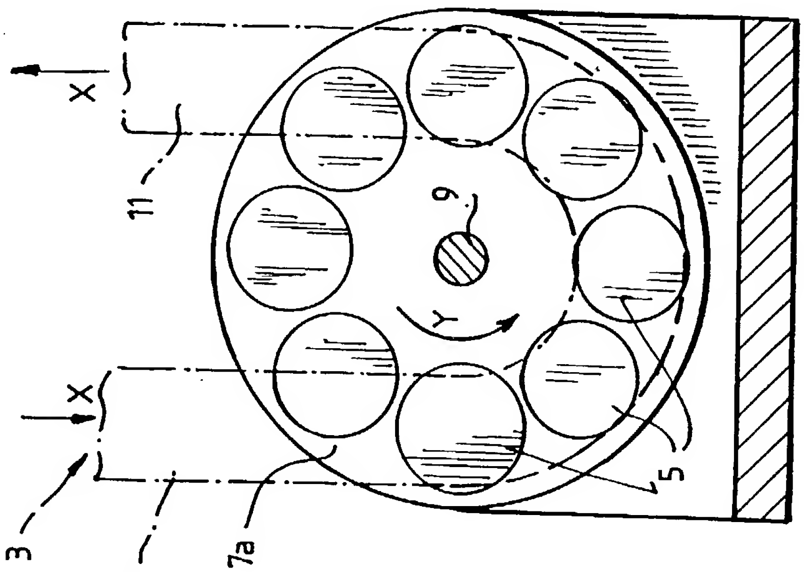


FIG. 2.

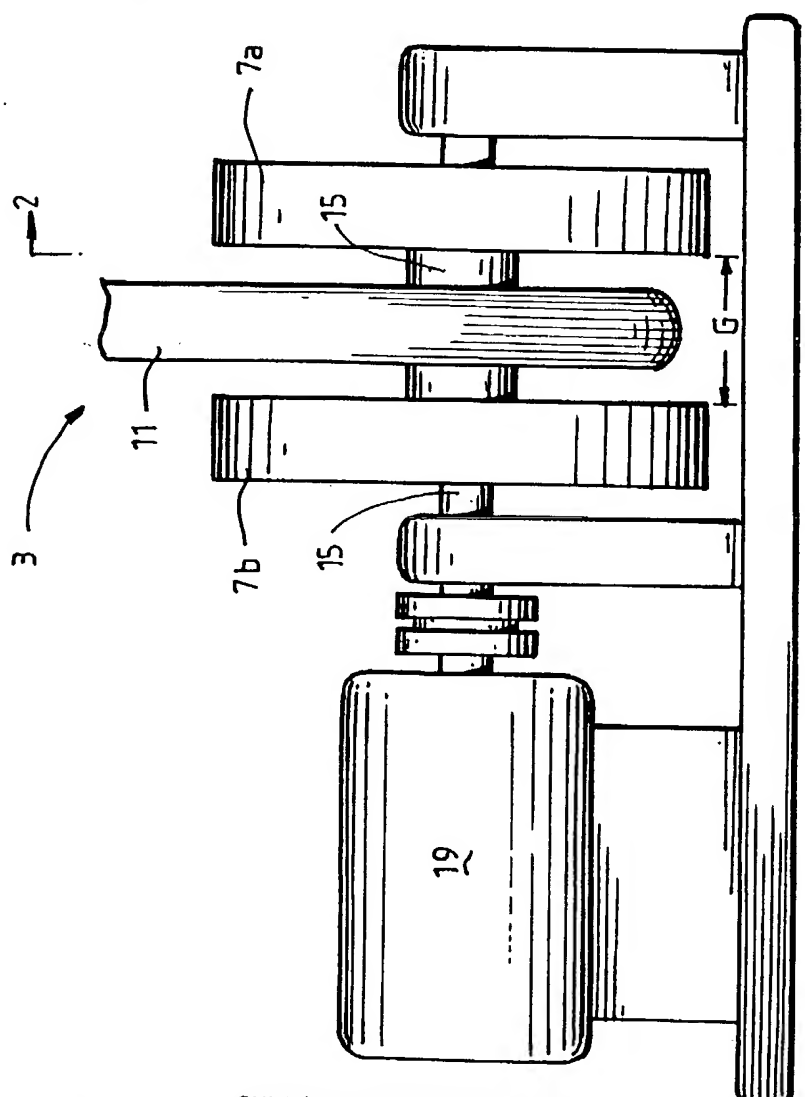


FIG. 1.

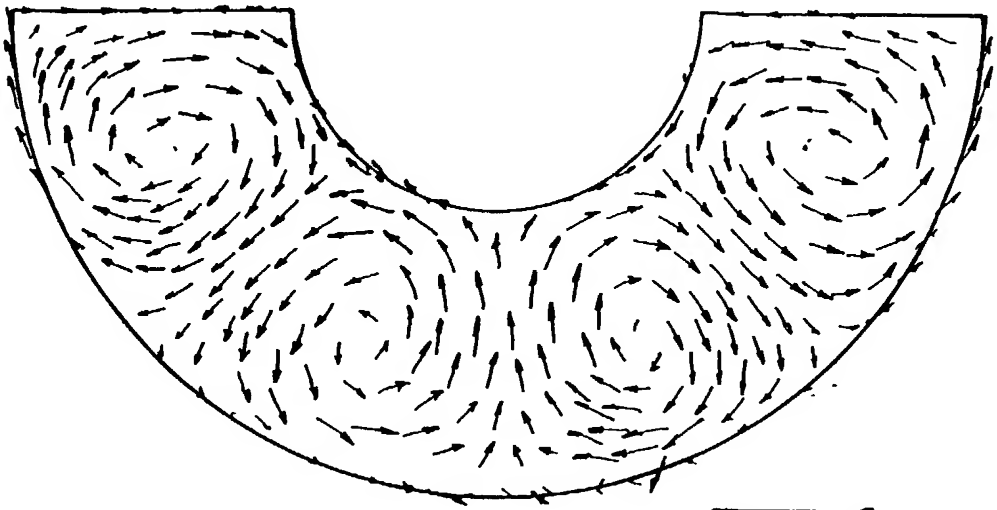
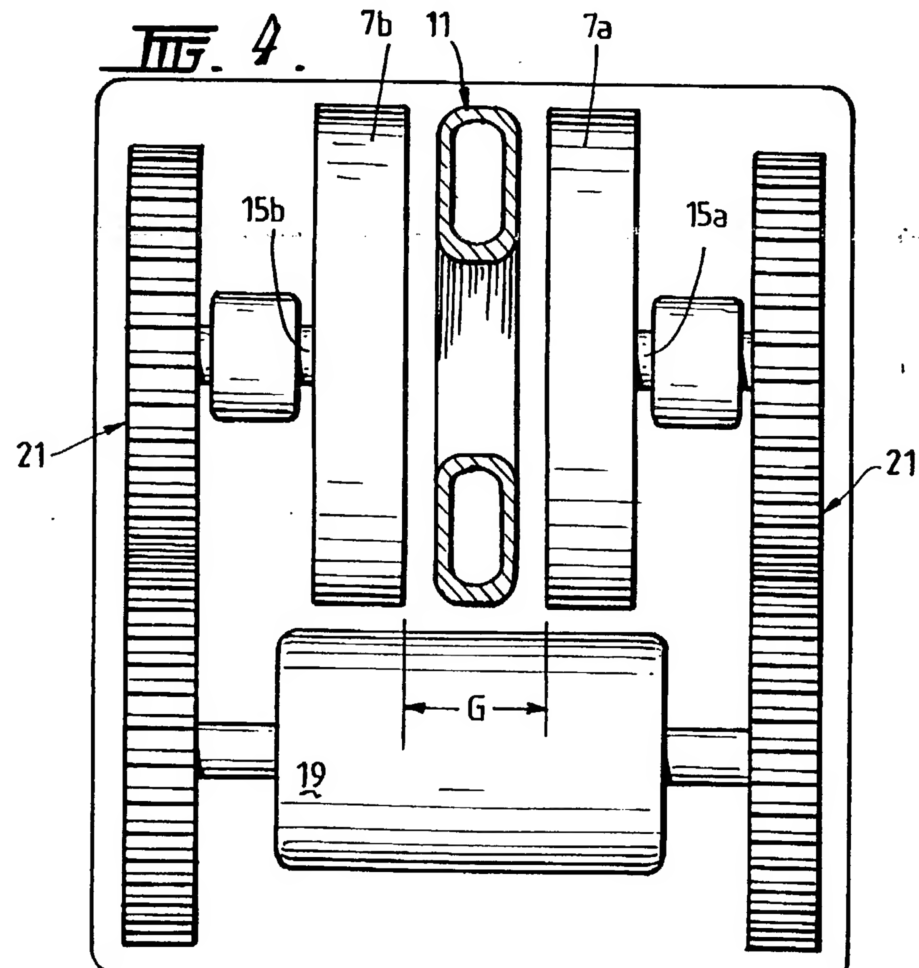


FIG. 3.

FIG. 4.



INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 97/00669

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl^{6}: H02K 44/04, H02K 44/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC H02K 44/02, 44/04, 44/06

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
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Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Derwent abstract accession No. 96-028969/03 class X11 RU 2035827 C1 (SVERD ENG TEACHING INST) 20 May 1995	1-20
A	WO 9308633 A (ARCH DEV. CORP) 29 April 1993 abstract	1-20
A	Patent Abstracts of Japan E-725, page 23, JP 63-274357 A (SHINKO ELECTRIC CO LTD) 11 November 1988 abstract	1-20

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Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 207526 A (HITACHI LTD) 7 January 1987 abstract	1-20

	International Application No.
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INTERNATIONAL SEARCH REPORT
Information on patent family members

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Patent Document Cited in Search Report		Patent Family Member			
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WO	9308633	US	5209646		
JP	63274357				
EP	207526	JP	62012371	US	4824329

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